

Effect of Thermal Treatments on the Mechanical Properties Enhancement of High Reliability Metallic Materials by Laser Shock Processing

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Abstract

Laser shock processing (LSP) is increasingly applied as an effective technology for the improvement of metallic materials mechanical properties in different types of components as a means of enhancement of their fatigue life behavior. As reported in previous contributions by the authors, a main effect resulting from the application of the LSP technique consists on the generation of relatively deep compression residual stresses fields into metallic components allowing an improved mechanical behaviour, explicitly the life improvement of the treated specimens against wear, crack growth and stress corrosion cracking. Additional results accomplished by the authors in the line of practical development of the LSP technique at an experimental level (aiming its integral assessment from an interrelated theoretical and experimental point of view) are presented in this paper. Concretely, experimental results on the residual stress profiles and associated mechanical properties modification successfully reached in typical materials under different LSP irradiation conditions are presented. In this case, the specific behavior of a widely used material in high reliability components (especially in nuclear and biomedical applications) as AISI 316L is analyzed, the effect of possible “in-service” thermal conditions on the relaxation of the LSP effects being specifically characterized.

I. Introduction

Laser shock processing (LSP) is increasingly applied as an effective technology for the improvement of metallic materials mechanical properties in different types of components as a means of enhancement of their corrosion and fatigue life behavior. Specially wear resistance, stress corrosion cracking susceptibility and crack propagation rate seem to be material properties specially improved by LSP treatments [1-4].

Although the technique was initially developed for the improvement of the fatigue crack resistance of materials used in the aeronautic applications (specifically Aluminum alloys), Titanium alloys and different types of stainless steels are being extensively investigated in the frame of different areas of application, especially the aerospace sector itself but also in the nuclear, automotive and biomedical sectors on the basis of the commercial availability of new powerful laser sources able to provide intensities exceeding the GW/cm^2 level [5-10].

In this paper, the special case of stainless steels and, more particularly, AISI 316L, is considered in view of the important number of applications of this material both in the energy sector (derived from its excellent corrosion resistance properties compatible with very convenient hot deformation (creep) resistance and good electron beam and laser weldability [11-12]) and its very promising applicability in the biomedical sector as structural material for external implants, combining excellent corrosion resistance, convenient surface deformability and good biocompatibility properties [13-14].

The proposed investigation on the effect of thermal treatments on the residual stresses fields induced by LSP is motivated because in some industrial applications, as i.e. in the case of nuclear power plants, materials are subject to repeated thermal stresses as a result of thermal gradients occurring during heating/cooling cycles (either in start-up/shut-down or in transient routine operations) close or directly in the creep range, what finally leads to an effective working life reduction due to creep-fatigue interaction regimes.

The study is considered to be relevant as the beneficial effects derived from induction of near-surface work-hardened nanoscale microstructures by different thermo-mechanical treatments can prevail and result in an effective improvement of components fatigue life only if the induced residual stresses fields remain stable during in-service mechanical loading and/or exposure to high temperatures and LSP has been identified as one of the treatments providing a higher degree of stability of these fields [15].

Although the problem of high-temperature fatigue behaviour and residual stress stability of laser shock processed stainless steels has been previously considered by other authors [16-17], a detailed analysis is required in order to correlate (1) the capability of the LSP treatment at different processing intensities to induce residual stresses fields into the treated material, (2) the thermal stability of these residual stresses fields depending on the generated microstructures and (3) the final fatigue life enhancement achieved in critical components after the thermal release motivated by high temperature working cycles (which is expected not to be complete according to the specific kind of material dislocations and cold work produced by the treatment). Additionally, the specific case of AISI 316L steel is considered to deserve a specific study in this sense in view of the referred important range of applications in which it is used as structural material.

From a concrete point of view, the effect of the application of different typical LSP intensities on the residual stresses fields introduced in this material, the thermal stability of these residual stresses and the final results in terms of fatigue life extension on standard specimens will be analyzed.

II. LSP Experimental setup and materials.

The practical irradiation system used for the experiments reported in this paper is essentially the same reported in previous contributions by the authors (see, i.e. [18-19]) and is schematically and photographically shown in Fig. 1. Using purified water as confining medium, the test piece is fixed on a holder and is driven by means of a robotized arm needed for the irradiation of extended areas of material following a pre-defined pulse overlapping strategy.

The laser beam (Q-switch Nd:YAG, 2.8 J/pulse, 9.4 ns FWHM pulse length, 10 Hz repetition rate) is conducted to the interaction area (typically circular spot 1.5 mm diameter) through a water confining layer and without any protective coating by means of a reflecting mirror and a focusing lens. The control of the purity of the confining medium is important in order to avoid the possible effect of impurities resulting from material ablation following the laser irradiation.

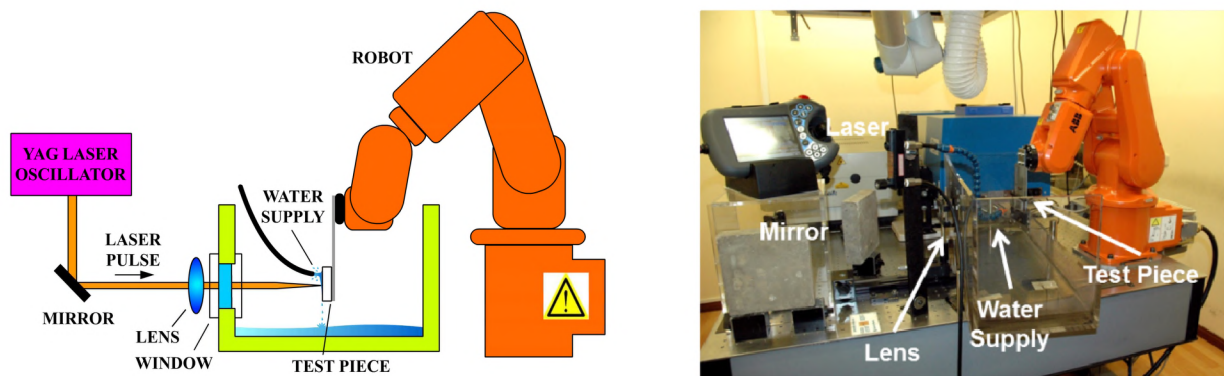


Figure 1: Schematic representation and photographic view of the LSP irradiation setup used in the reported experiments.

The LSP experiments reported in this paper were performed on AISI 316L steel with the composition shown in Table 1. The as-received material, in the form of 6 mm thick plates, had been hot rolled and solution annealed between 1050 and 1100°C. The initial mechanical properties of the treated material were experimentally determined using dog-bone type specimens according to ASTM E 8M standard [20] and presented in Table 2.

Table 1: Percent Composition of AISI 316L Steel Used in the Reported Experiments

Element	C	Cr	Ni	Mo	Mn	Si	N	P	S	Fe
% wt	0.018	16.815	10.086	2.044	1.294	0.458	0.047	0.032	0.003	Bal.

Table 2: Initial Mechanical Properties of AISI 316L Steel Used in the Reported Experiments

Property	Value
Elastic Modulus [GPa]	177.2
Offset Tensile Yield Strength [MPa]	355.4
Ultimate Tensile Strength [MPa]	633.6

For the analysis of the stability of the residual stresses fields induced by LSP, 40 mm x 40 mm samples were one-side treated according to the experimental variable overlapping procedure originally defined by the authors [18-19]. For the reported analysis, two equally X-Y spaced overlapping schemes were selected implying respective equivalent overlapping densities (EOD's) of 900 and 1600 pulses/cm² (respective overlapping pitches of d=0.33 mm and d=0.25 mm).

For the analysis of the fatigue life enhancement induced by the LSP treatment, both in pristine and thermally aged forms, standard dog-bone type specimens used for fatigue test were machined in accordance with ASTM standard E466 [21], with 150 mm length. For these specimens, the LSP treatment was applied on both sides over approximate areas of 35 mm x 20 mm in their central reduced zone following a sweeping strategy progressing transversally to the larger dimension.

III. Experimental results

For the proposed analysis, both types of samples were LSP treated according to the two referred parametric conditions and subject to thermal aging in order to evaluate the RS's fields stability and the resulting performance under fatigue life tests. According to the practical working conditions of a great proportion of AISI 316L components, a thermal aging temperature of 500°C maintained over 8 hours (considered as sufficient for pure thermal stresses release) was selected as testing reference. No experimentation beyond this temperature was made in view of the well know drop in tensile stress and creep onset starting at about 550°C for the considered material [11-12].

Figure 2 shows, i.e., two of the considered specimens treated at EOD = 900 pulses/cm² without and with application of thermal aging.



Figure 2. LSP treated specimens at EOD = 900 pulses/cm² without and with thermal aging at 500°C during 8 hours.

1. Residual Stresses Fields

Residual stress distributions reached in the LSP treated specimens were determined according to the ASTM E837-01 Standard Test Method for Determining Residual Stresses by the Hole Drilling

Strain Gage Method [22]. Strain gage rosettes CEA-13-062UM-120 along with a Vishay Measurements® RS-200 milling guide were used.

Fig. 3 shows the in-depth profiles obtained for LSP-induced Mohr maximum (i.e. minimum in absolute value) RS's with the two considered LSP treatment conditions before and after application of thermal aging.

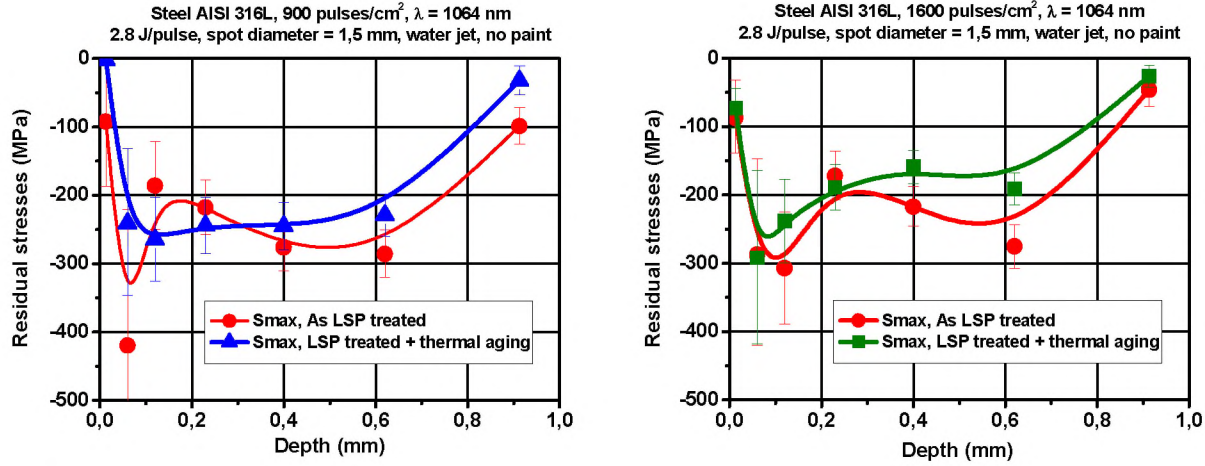


Figure 3. In-depth profiles obtained for LSP-induced Mohr maximum (i.e. minimum in absolute value) RS's with LSP treatment at EOD = 900 pulses/cm² (left) and EOD = 1600 pulses/cm² (right) before and after application of thermal aging at 500°C during 8 hours.

The effect of the applied heat treatment can be clearly observed in both cases as both a decrease of the maximum compressive residual stress resulting in the treated material and a general softening of the level of compressive residual stresses available in the material depth explored by the RS's determination method. Both facts imply in practice a certain degree of compressive RS's relaxation that, undoubtedly, must have a certain effect on the material fatigue life, but it is also noticeable that the RS's release is by no means complete, what can be attributed to the special kind of thermally irreversible dislocations induced by the LSP treatment as anticipated in ref. [15].

Additionally, in the case of EOD = 1600 pulses/cm² (a LSP treatment intensity considered as a certain threshold for AISI 316L in order to produce RS's fields deep enough to provide an effective protection against crack propagation), the effect of the applied thermal cycle is not enough to relax completely the minimum value of compressive residual stress induced by the treatment at the material surface, maintaining at the same time a reasonable level of compressive values through the material depth close to the surface (up to 1 mm according to the determination method), a result that allows to anticipate a certain improved behaviour of the specimens treated under this condition in fatigue life tests.

2. Fatigue life

Fatigue tests of LSP treated specimens according to the two specified treatment conditions both prior and after thermal aging were conducted in order to evaluate the degree of permanence of the protective effect of the LSP treatments under such relaxation process. The corresponding tests were carried out on a MTS 810 servo-hydraulic system at room temperature in air. The loading axis was parallel to the rolling direction of the samples and the test was performed in load-control. To ensure a precise alignment of the specimen gripping fixtures, an alignment module supplied for MTS controlled with an specific alignment system software was used in order to allow a highly accurate loading of the specimen along its longitudinal axis with minimal bending strain. The fatigue results were presented using the classic S-N fatigue (Wöhler) curve format with stress amplitude, S_a , plotted as a function of cycles to failure, N , establishing as fatigue limit the loading for which the

material reaches 10^6 cycles without failure. The testing was limited to tension-tension loading with mean stress conditions described by $R = 0.1$ and a sinusoidal waveform of 10 Hz.

In figure 4, the referred S-N curves corresponding to the two specified LSP treatment conditions are presented compared to the reference of the pristine AISI 316L material in the same experimental testing conditions, both after pure LSP treatment and after LSP treatment followed by thermal aging in the specified conditions.

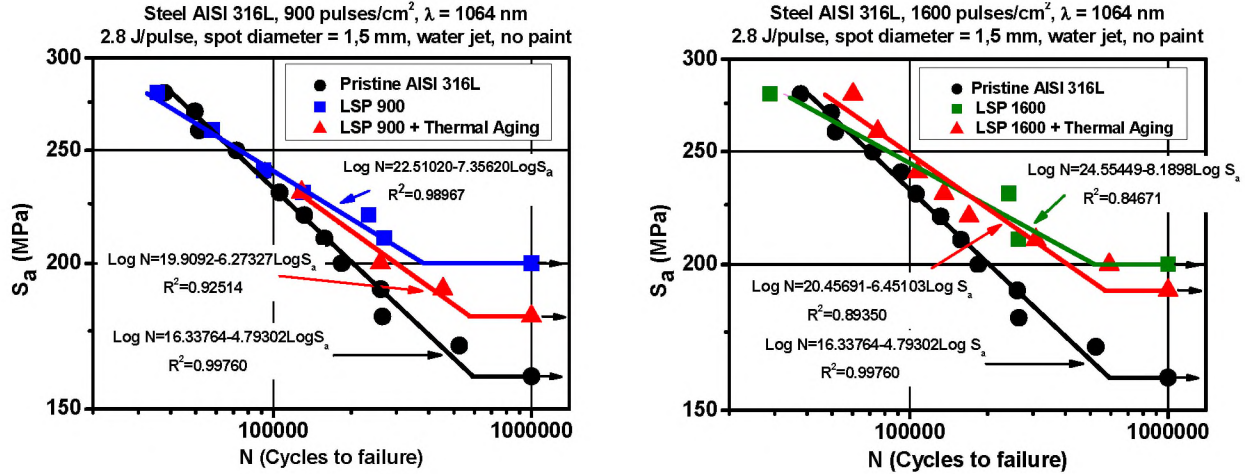


Figure 4. S-N curves corresponding to comparison to pristine AISI 316L material of LSP treated specimens and LSP treated specimens subject to ulterior thermal aging at 500°C during 8 hours. Left: Results for EOD = 900 pulses/cm². Right: Results for EOD = 1600 pulses/cm².

In both curves, the improvement of fatigue life provided by the LSP treatment at both EOD's can be clearly observed (rise in runout amplitude from about 160 MPa to about 200 MPa in both cases) but, additionally and most important for the prospects of the present work, a maintenance of the protective effect provided by the LSP treatments after the application of the considered thermal aging cycle can be clearly observed also in both cases.

Within the limitations due to statistical factors in the performed tests, even in the case of EOD = 900 pulses/cm², an increase of about 12.5% (from 160 to 180 MPa in runout amplitude over the pristine AISI 316L) is still observed to be maintained after thermal aging and the increment is even higher (increase of about 18.75% in runout amplitude over the pristine material face to the 25% obtained without thermal aging) in the case of EOD = 1600 pulses/cm² treatment (in a consistent way with the observed better maintenance of the compressive RS's fields reported in the previous section).

IV. Discussion

In view of the frequent need to protect high reliability metallic components in thermally aggressive environments, the capability of the LSP treatment to maintain its demonstrated protective character against fatigue failure in service conditions of thermal aging has been analyzed. In view of its important domain of applications in the energy and biomedical sectors, the behavior of the AISI 316L stainless steel has been studied as a representative sample material.

Experimental determination of residual stresses fields in the LSP treated materials prior and after the application of characteristic thermal aging cycles has confirmed an important degree of maintenance of such fields presumably due to the specific character of the predominantly irreversible mechanical dislocations induced by the LSP treatment and as indicated by several authors in the literature. Of course, the effect is much more evident for LSP treatment intensities above a certain treatment intensity threshold implying the generation of such type of dislocations.

In full consistency with this fact, the improvement of fatigue life of standard test specimens treated by LSP has been observed (within the limits of the statistical uncertainties associated to testing procedures, but with a clear tendency) to remain to an appreciable degree after the application of a characteristic thermal aging cycle.

Consequently, and although needing further study for a more precise evaluation of the practical working limits for in-service reliable performance of components of the analyzed material, the clear conclusion can be extracted of the suitability of the LSP technique for the practical improvement of the fatigue life of high reliability components in AISI 316L (in a similar way to the case of other characteristic materials previously studied by the authors [18-19]) even in conditions implying service temperatures in the range of at least 500°C.

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